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# SIMULATION OF REENTRY VEHICLE LASER COMMUNICATIONS IN AN 8000-KILOWATT PLASMA FACILITY

by

T. A. Barr, Jr.
Charles Cason

November 1968

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U.S. ARMY MISSILE COMMAND
*Redstone Arsenal, Alabama*





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## ABSTRACT

Laser communications have been proposed as one way to solve the "radio blackout" problem during the reentry of a manned vehicle. The U. S. Army Missile Command 8000-Kilowatt Plasma Facility was used in a set of experiments to simulate the conditions expected during the reentry of a high-speed vehicle. This experimental study was designed to simulate a typical theoretical Apollo test vehicle reentry trajectory. No plasma effects on the transmitted laser beam were expected or observed. The high temperature gradients and anticipated gas density variations in the flow field were thought to be potential sources of local index-of-refraction fluctuations.

By variation of the plasma facility parameters to lower the enthalpy, the Reynolds number, or both, a satisfactory simulation of conditions just before the termination of "radio blackout" was obtained. The region of the "reentry corridor" simulated in this investigation is near a 60-kilometer per second velocity. A 0.09-meter diameter flat disk model oriented normal to the flow field was used in experiments to determine the degradation of an He-Ne laser beam modulated by a 20-kilohertz signal on a 40-megahertz carrier. Harmonic analysis of the modulation showed a small modification of the signal. A flat plate 1 meter long was also used in experiments to determine beam deflection by the flow field due to index of refraction fluctuations. Beam deflection was $< 10^{-5}$ radians.

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## ILLUSTRATIONS

## 1. Summary

Laser communications have been proposed as one way to solve the "radio blackout" problem during the reentry of a manned vehicle. The U. S. Army Missile Command 8000-Kilowatt Plasma Facility[1,2] was used in a set of experiments to simulate the conditions expected during the reentry of a high-speed vehicle. This experimental study was designed to simulate a typical theoretical Apollo test vehicle reentry trajectory. No plasma effects on the transmitted laser beam were expected or observed, since the cutoff frequency due to electron collision rates was calculated to be in the microwave region and not in the optical or infrared region. However, the high temperature gradients and anticipated gas density variations in the flow field were thought to be potential sources of local index-of-refraction fluctuations. These fluctuations may generate scintillation effects in the laser beam which would be expected to reduce the effectiveness of laser communications.

The limitation of maximum power in the plasma facility flow field, approximately 4 megawatts, prevented simultaneous duplication of the desired Reynolds number ($R \approx 7 \times 10^4/m$) and the stagnation point enthalpy $\left(h/RT_o \approx 100\right)$. However, by variation of the plasma facility parameters to lower the enthalpy, the Reynolds number, or both, a satisfactory simulation of conditions just before the termination of "radio blackout" was obtained. The region of the "reentry corridor" simulated in this investigation is near a 60-kilometer altitude and 3.9-kilometer per second velocity. The Reynolds numbers were based on a characteristic length of 1 meter for the vehicle and 0.1 meter for the model. A flat disk model, normal to the plasma facility flow stream, was used to generate the required local flow field for the laser experiments. The disk diameter, 0.09 meter, was determined by the plasma facility flow-field blockage parameter; this also established the characteristic Reynolds number length ($\ell \approx 0.1$ m) for the experiments. The disk was followed by a cylindrical afterbody of smaller diameter approximately 25 centimeters long containing instrumentation. The cylinder also had a pair of windows situated so the laser beam could pass through the flow field immediately behind the disk. An amplitude modulated helium-neon laser was used as a signal source with a photomultiplier tube as a detector. Model stagnation pressure and transmitted

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[1] Barr, T. A., Jr., "The AMICOM 8,000 kW Plasma Facility," Fourth Space Congress, Cocoa Beach, Florida, April 1967, pp. 25.1-25.9.

[2] Barr, T. A., Jr., and Cason, C., "Multiple Arc Performance in an 8,000 kW Plasma Facility," Proceedings of the Eighth Symposium on Engineering Aspects of Magnetohydrodynamics, Stanford, California, March 1967, pp. 145-147.

laser signals were recorded on an analog tape recorder. A frequency spectrum analyzer was used for analysis of the data.

The experiments performed to date have been in the laminar flow regime, and the test results indicate that laser communications should be satisfactory. However, a residual perturbation in modulated laser signals appears to exist in this regime, even after account is taken of the perturbations introduced by the experiments. This indicates that some low-level scintillation effects may be present even for laminar flows at high total gas enthalpy. These effects may become important for the high-velocity turbulent flow case.

## 2. Experiment Design

The purpose of the research reported here was twofold. First, it was intended to determine the simulation capability of the plasma facility for reentry vehicle laser communications experiments. Secondly, it was intended to measure the effects of undetermined parameters which might influence laser communications from the reentry vehicle to a ground station for the specified plasma facility simulation regions. The first part required the comparison of the plasma facility's capabilities to the requirements imposed by the vehicle's trajectory. The second part was the experimental measurement of the laser signal's response characteristics after transmission through a model tested in the plasma facility. This test included measurements of modulation distortion and/or induced modulation and refraction effects.

A reentry trajectory similar to that of an Apollo test vehicle was chosen, since its relatively low velocity would maximize opportunities for useful laboratory simulation. The trajectory selected for study (Figure 1) gives the typical features for a command module reentry. The dashed line indicates the theoretical radio communications blackout region for 10-centimeter electromagnetic waves. The blackout region for longer wavelengths is almost the same, because of the rapid decline in free electron concentration for this portion of the trajectory. The lowest velocity for which laser communications would be significant is shown (Figure 1) to be about 3.9 kilometers per second. This is not a lower limit, because this calculation neglected the contributions of free electrons generated by ablation products, which is known to be an important fact at lower velocities. Effects of ablation were not considered important in this analysis because a nonablating model was used in the experiment.

The plasma facility's capability range is also indicated in Figure 1. This capability region is based on the approximation that the flow enthalpy, $\frac{1}{2}v^2$, is half the total enthalpy. Experimental evidence indicates this to be a

useful and valid approximation when used for determining the limits of capability from equilibrium calculations. The lower bound is the power limit of 4 megawatts in the flow field, i.e., $\frac{1}{2}\rho v^3 = 4$ MW, when $\rho$ and v are the freestream density and velocity, respectively. The high and low enthalpy limits are variable to some extent, but a specific total equilibrium enthalpy of $h/RT_0 = 300$ is near the maximum available. The low enthalpy limit is undetermined, but below $h/RT_0 = 75$ many other facilities become useful. In order to satisfy the 3.9-kilometer per second velocity condition, the specific flow-field enthalpy required is $h/RT_0 = 96.5$; therefore, the total specific equilibrium enthalpy must be approximately $h/RT_0 = 200$.

The simulation parameter chosen for these experiments was the Reynolds number. This choice was made because the expected effects would be generated by turbulence in the boundary layer next to a laser "porthole" in the reentry vehicle. The free-flight environment was used to calculate a set of Reynolds numbers for a characteristic dimension of 1 meter. These are shown in Table I. Similar calculations were made for one of the most highly powered operating conditions available by the plasma facility. In the free-flight case the Reynolds number is simply

$$Re = v\ell/\nu \ , \tag{1}$$

where

$v$ = velocity (m/sec)
$\ell$ = characteristic length (m)
$\nu$ = kinematic viscosity ($m^2$/sec).

Kinematic viscosity was read directly from tabulated values.[3] For the plasma facility environment, a slightly different version of the Reynolds number equation was used. Here

$$Re = \rho v \ell / \mu \ , \tag{2}$$

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[3] U. S. Army Ballistic Missile Agency, Redstone Arsenal, Alabama, Numerical Tables of Atmosphere Parameters Based on the ARDC Model Atmosphere, 1956, February 1958, Report No. DA-TN-197.

TABLE I. REYNOLDS NUMBER PER METER AS A FUNCTION OF THE TRAJECTORY PARAMETERS

| Altitude (km) | Velocity (v) (m/sec) | Kinematic Viscosity ($\nu$) ($m^2$/sec) | Reynolds Number per Meter |
|---|---|---|---|
| 90 - 60 | 9350 | $3.28^{-2}$ to $8.69^{-2}$* | $\approx 10^5$ |
| 52 | 9000 | $2.07^{-2}$ | $4.36^5$ |
| 43 | 8000 | $6.43^{-3}$ | $1.24^6$ |
| 40.5 | 7000 | $4.46^{-3}$ | $1.57^6$ |
| 40.5 | 6000 | $4.46^{-3}$ | $1.35^6$ |
| 43 | 5000 | $6.43^{-3}$ | $7.77^5$ |
| 61 | 4000 | $5.21^{-2}$ | $7.86^4$ |
| 39 | 3000 | $3.56^{-3}$ | $8.43^5$ |
| 32 | 2000 | $1.18^{-3}$ | $1.70^6$ |

*NOTE: Exponents represent powers of 10.

where

$\rho$ = density (kg/$m^3$)
$\mu$ = viscosity (kg/m sec).

The viscosity is calculated from the given expression

$$\mu = \frac{146\ T^{3/2} \times 10^{-8}}{T + 110} , \qquad (3)$$

where T is in degrees Kelvin (°K). The Reynolds number per meter for the plasma facility at a point near the peak on Figure 1 at 3.9 kilometers per second is best described in terms of one of the plasma facility's specified operating points. For this example

$$\rho = 1.8 \times 10^{-4}\ kg/m^3,\ v = 3750\ m/sec,\ and\ T = 500°K.$$

Viscosity, $\nu$, is first calculated from equation (3). This value of $\mu$, 2.48 $\times 10^{-5}$ kg/$m^2$ sec, combined with the above values of $\rho$ and v, gives a Reynolds number of 2.78 $\times$ $10^4$ per meter. The difference between the plasma facility conditions and the real flight environment would be small if a full-size model (or models of vehicle sections) could be used. Velocities are fairly close

together, 3900 meters per second in the real case and 3750 meters per second in the plasma facility. The facility simulation parameter, the Reynolds number of $3 \times 10^4$ per meter, is within a factor of three of matching the $7 \times 10^4$ per meter required for exact duplication.

### 3. Equipment Setup

The experimental test model has a characteristic dimension of about 0.1 meter, so the Reynolds number for this model is about $3 \times 10^3$. In order to favor the development of some form of turbulence, the model was constructed with a flat plate front followed by a base section of smaller diameter. The model shown in Figure 2 was centered on the flow-field axis. The plasma facility test limit due to blockage was used to govern the actual model size. This limit is

$$C_D \, Am/Af < 0.11, \qquad (4)$$

where

$C_D$ = model drag coefficient
$Am$ = frontal area of the model
$Af$ = cross section of the flow field.

A maximum model diameter of 0.11 meter satisfies this limit. The model also shows the window behind the flat plate which was used to transmit the helium-neon laser light. A quartz plug in the face plate was available for transmission of the laser beam upstream through the plasma facility nozzle but was not used in this set of experiments. Figure 3 shows the disassembled model. The folded out (lower portion) shows the impact plate, water cooling tubes, the impact pressure tube and the impact pressure transducer. The upper portion contains the mirror mount (not used in these experiments), the sapphire windows, the Wilson double probes, the the probe's drive mechanism, the vibration transducer, and the probe's signal conditioning equipment.

### 4. Modulation Experiments

The arrangement of the equipment components is shown in Figure 4. Data collection and handling can be followed by signal tracing through the system as follows:

a) A radio frequency, 40-megahertz exciter drives the helium-neon laser used (Spectra Physics Model 115).

b) The laser output goes through an interferometer-type modulator which is driven at 20 kilohertz. This produces an amplitude modulation on the laser beam.

c) The modulated laser beam passes, in turn, through the plasma facility's observation window into the test section, one side of the flow field, the model's oblique shock wave, the model's boundary layer, the model, via the portholes which have $^1/_{16}$-inch thick sapphire windows, and out the other side of the model through the same type of environment as the inlet side.

d) The laser beam then passes through a narrow band interference filter ($\Delta\lambda \approx 1.5\ \mu m$) and, if required, one or more "grey" attenuation filters, and an iris diaphragm stop.

e) The laser beam with any interference effects is then detected by a photomultiplier tube.

f) The alternating current output signal of the photomultiplier is then fed into an oscilloscope and/or a loop tape recorder for eventual frequency spectrum wave analysis. When the data are read out on the oscilloscope, amplitude of the modulation envelope versus time is measured. When the wave analyzer is used, the amplitude of the various frequency components is measured and averaged over the measurement time.

Figure 5 shows a photograph of the model being tested in the plasma facility. Flow is from left to right. The stagnation zone and the shock wave are visible. The vertical shaft of light is caused by an electron beam used in diagnostics of the flow field.

## 5. Data and Analysis

The oscilloscope data serve a valuable qualitative check on the frequency spectrum analyzer results. Deductions based on quantitative spectrum analyzer data were supported by these oscilloscope data. Each experiment required the measurement of the effects from each potential source of interference separately. The combined effects including those from the plasma facility flow field were then obtained. With all laser equipment operating, pre-test oscilloscope photographs were made which verified that signals were being transmitted through the system. Next, oscilloscope photographs were made under identical analytical test conditions but with various functions

of the plasma facility in operation. Minor adjustments in equipment setup were required, e.g., to eliminate a vibration transmission to the laser when the plasma facility's cooling water pumps were operating. Also, it was shown that the plasma facility's capacitor discharge-type ignition starter had no influence on the laser signal read by the photomultiplier tube. Figure 6 shows the modulation envelope with only the laser equipment on, the oscilloscope trace of the photomultiplier tube 20-kilohertz output light signals before a test. The time scale is 1 second per division. Figure 7 shows the laser signal oscilloscope record with plasma facility in operation. The oscilloscope trace of the photomultiplier tube 20-kilohertz output light signals during a test also has a time scale of 1 second per division. The small direct current level displacement during the 4.5-second test and the noise modulating the signal after the controller settles down is discernible from the photograph. The laser signal modulation envelope indicates the start of operation by the large transient near the left margin. The periodic (≈ 3-Hz) modulations following start-up are related to the power controller equipment frequency as modified by the electrical effects from the main power generators for the plasma facility. By the end of the second second of operation the starting transients have damped almost to zero, and the true plasma interference may be seen. This interference, although weak, is clearly seen as the noisy edge riding on the modulation envelope.

Quantitative analysis of the frequency content was made with the spectrum analyzer. This shows essentially the same effect as seen in the oscillographs. Because of limited running time, only a small portion of the available spectrum was analyzed during each test. The frequency spectrum analyzer was fed signals from the loop recorder after the run for more complete analysis. The range of detailed spectrum analysis was between 19 and 21.5 kilohertz. This is centered about the modulation frequency but is far above the mechanical vibration frequency or even the flow-field turbulence frequency. Results obtained from this study of the present data indicate a low-frequency noise superimposed on the modulation envelope and a high-frequency component added near the modulation frequency. The spectrum analyzer output is shown in Figure 8. Spectrum analyzer records of the photomultiplier tube output light signals are taken from the loop tape recorder. In the top trace, the record was taken during the test shown in Figure 6 with no arc jet operation. In the bottom trace, the record was taken during the test shown in Figure 7 during the arc jet operation only. Photocurrent is plotted in terms of gain in decibels. Records taken during plasma facility runs show miscellaneous spikes of a few decibels occurring at apparently random frequencies. Actual frequency structure of the modulated light signal has some occasional noise components blended into it, but they are always at low level. The way in which these additional frequencies modify the laser beam has not been determined. A suitable mechanism having the necessary nonlinearity to couple energy directly into the laser electromagnetic wave has not been visualized. The laser

frequency and the modulation frequency are both very far from the plasma cut-off frequency. A portion of the noise is attributed to the low but finite radiation from the plasma around the model.

A second set of experiments was performed to measure the effect of plasma radiation on the laser detector output. In this case all laser equipment was turned on and laser signal transmission and system signal gain were checked. Then, since the laser beam was physically blocked before it entered the plasma facility's window, the detector output was measured on an oscilloscope while the plasma facility was operated. Figure 9 shows the effects obtained. Oscilloscope trace of the photomultiplier tube output signals here show a blocked laser beam during a plasma facility run. A small direct current displacement of a uniform noise modulated output signal is seen. Comparison to Figure 7 gives a qualitative measure of the plasma-generated effects on the light signals. To determine the quantitative contribution of this noise source to the laser communications signal would require a series of tests having adjustments in the filter transmission band and/or in the spacing between the model and detector.

A number of other experiments were performed with use of the same equipment but at different modulation frequencies, down to 100 hertz. All these appeared to be compatible with the 20-kilohertz result already discussed, viz., that some distortion of the laser signal occurred with the plasma facility running. A portion of this can be attributed to plasma radiation which, in the real case of laser communications from a reentry vehicle, could be made to be of no consequence.

### 6. Scintillation Experiments

A possible alternate explanation for the modulation distortion lies in the scintillation of the laser beam, i.e., in the small angle deflections due to thermal and/or density gradient fluctuations in the gas around the reentry vehicle. Experiments were performed to study this effect. The detector used in the previous experiments was covered with an iris diaphragm in front of a collimator to reduce stray light. The diaphragm opening was just large enough to permit the beam to pass through it almost unattenuated when axially centered. Any angular displacements of the laser beam by density refraction fluctuations would produce shadowing of parts of the detector as the laser beam's axis is modulated, which then would generate amplitude modulation in the detector output signal.

During actual field tests, the indirect plasma effects, those due to radiation from the plasma at the laser frequency, are expected to disappear, since these are attenuated by the square of the distance. However, the direct plasma effects, those due to beam-axis modulation and signal-level or frequency interactions, will continue to persist.

A third set of experiments was performed in an effort to extend the range of simulation to cover some portion of the turbulent flow field. These experiments were not successful in that the procedure used did not generate the required turbulence. The experiment consisted of placing a flat plate in the flow field and shining a laser beam ($\approx$ 0.059-inch diameter) about $^1/_4$ inch above the surface of the plate at 24 inches downstream from the leading edge of the plate. Photographs were made of the laser beam and flat plate without the plasma facility running, with the plasma facility running, and with a boundary layer trip wire on the plate and the plasma facility running. No disturbance of the laser beam was noted photographically in any case. A typical photograph of this setup is shown in Figure 10. The laser beam appears as a bright spot just above the plate. The shock wave around the plate is noteworthy. The trip wire near the forward edge is there to encourage turbulence in the boundary layer. The trip wire is a piece of $^1/_4$-inch diameter copper tubing bent around the plate. Negative results were indicated throughout these tests, so no additional effort to instrument the experiment was made.

Theoretically the local index of refraction fluctuations in the hot boundary layer of a reentry vehicle could lead to a fluctuation in the direction of a laser beam transmitting information from the vehicle to the ground. An idealized picture of this problem is shown in Figure 11. Turbulence in the boundary layer generates a refractive index change which deflects the laser beam. In such a case one might visualize an optical tracker in the vehicle. This would be used to point the laser at a position on the ground which would probably be identified by an intense light (e.g., a laser) pointed in the general direction of the reentry vehicle. Automated pointing systems would be required eventually for both the vehicle communications laser and the ground station identification light. Atmospheric scintillation is ignored in this study, and because of geometric considerations, it is assumed that the boundary layer fluctuations will not cause serious problems in visually localizing the ground station. (This may not be a good assumption in some cases or in certain portions of the reentry trajectory.) This leaves the problem of scintillation of the vehicle laser as seen at the ground station.

The calculation of expected scintillation angles is beyond the scope of this report; however, the following points need to be considered.

a) The trajectory shown in Figure 1 indicates that a reentry vehicle may pass through several flow regimes during the radio blackout portion of reentry. Low-density laminar flow is first indicated. This is followed by a high-velocity transition flow, a turbulent flow, a low-velocity transition flow and finally, just before the end of blackout, a low-velocity laminar flow. Within these regimes are laminar boundary layers, vortex shedding of the boundary layers, and turbulent boundary layers. In both the vortex and turbulent conditions it is possible to have fluctuating temperature and density along the line of sight of a laser beam used for communications.

b) The extent of the beam deflection may be determined approximately if data can be obtained on the size, frequency, density, and temperature of the flow-field fluctuations. Either experimental data or theoretical calculations are difficult to obtain for these properties.

c) Given the information in a) and b) above, the laser beam can be traced in succeeding moments of time. Thus, fair approximation of the beam deflection and change of direction in time can be obtained.

The deflection problem is like that of the refraction of light by flames. Figure 12 shows the geometry for the simplest approximation to such a refraction angle calculation.[4] In this case a ray of light is traced through a cylindrical zone (flame or vortex) of hot gas. Equation (5) gives the total angle of deflection for two refractive changes as shown in the figure $\left({}_c n_h\right.$ is the ratio $\left. n_c/n_h\right)$. A truly accurate picture would require a varying index of refraction and a cumulative or integrated deflection angle. This region has an index of refraction $n_h$ where the surrounding medium has an index of refraction of $n_c > n_h$.

$$\theta = 2 \left[ \sin^{-1} \left( \frac{h}{a \; {}_c n_h} \right) - \sin^{-1} \left( \frac{h}{a} \right) \right] . \tag{5}$$

Experiments were performed to show if such a scintillation effect would appear in the plasma facility. The same laser source and model were used as before. The detector was removed, and the laser beam was allowed to fall on a photographic plate about 20 meters from the model. The laser was adjusted to

[4] Weinberg, F. J., Optics of Flames, Chapter 1, Butterworth & Co., Ltd., Belfast, 1963.

focus on the plate. Figure 13 shows the setup for these experiments. The focused laser light was in the shape of a small cross as shown in Figure 14, which is taken from measurements of photographs obtained with the equipment shown in Figure 13. Photographs of the beam were made with the plasma facility both running and not running. An enlargement or "fuzzing" of the laser beam image in the running photograph could be interpreted as a scintillation effect. The photographs were accurately measured, and practically no change was noted. However, if the horizontal enlargement of the image is real (Figure 14) and can be attributed to refraction, this means about $10^{-5}$ radian refractive deflection was observed. Figure 15 shows the appearance of the laser source as seen from the camera location. The laser beam appears as a bright spot enlarged by refraction from the various surroundings. By appearance (and calculation) the plasma facility was operating in a laminar flow condition. This corresponds roughly to the low-velocity laminar flow regime for the reentry vehicle.

## 7. Conclusion

From the experiments reported here it appears that laser communications from a reentry vehicle to the ground is feasible insofar as laminar flow-field conditions are concealed. The experiments were limited to the low-speed laminar flow regime because of the plasma facility's limitations. Within this limit only minor frequency interference was noted (Figure 8). Angular dispersion was also found to be negligible.

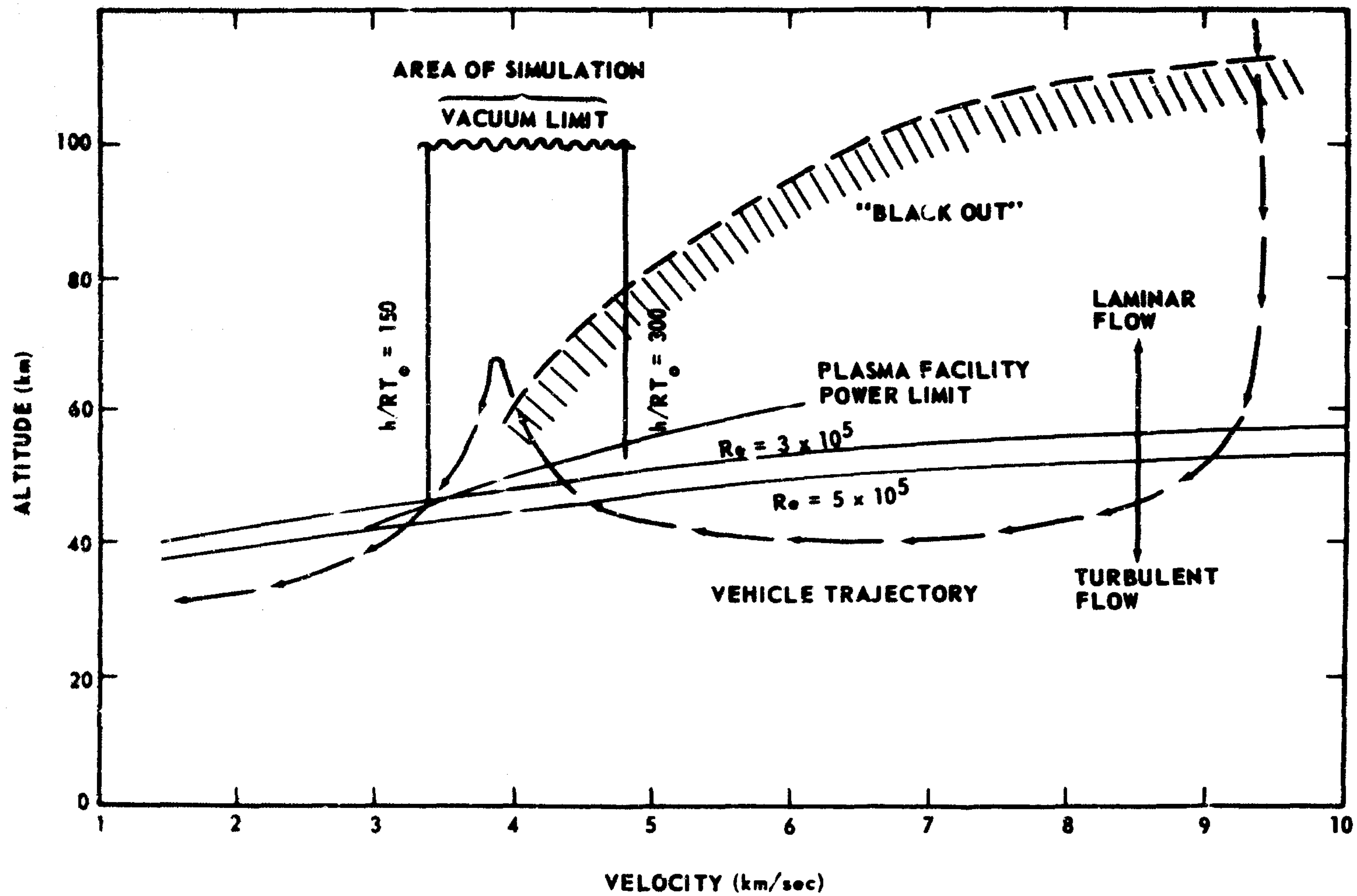



FIGURE 1. VELOCITY-ALTITUDE GRAPH FOR REENTRY OF APOLLO-TYPE TEST VEHICLE

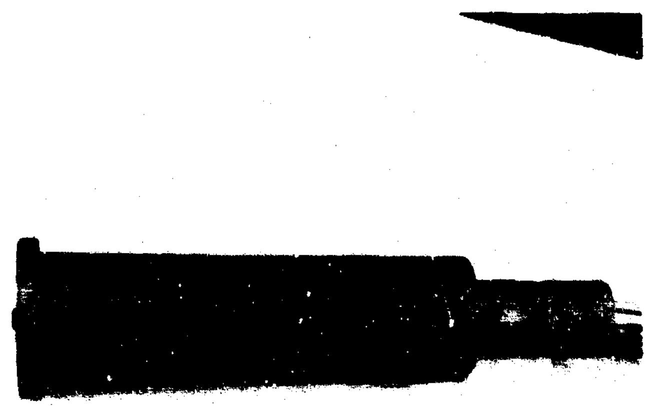


FIGURE 2. MODEL USED IN PLASMA FACILITY EXPERIMENTS

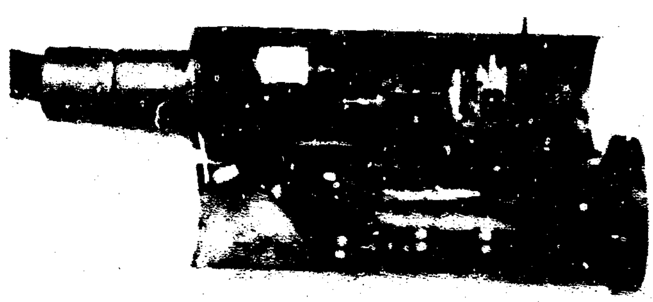


FIGURE 3. MODEL OPEN TO SHOW CONTENTS

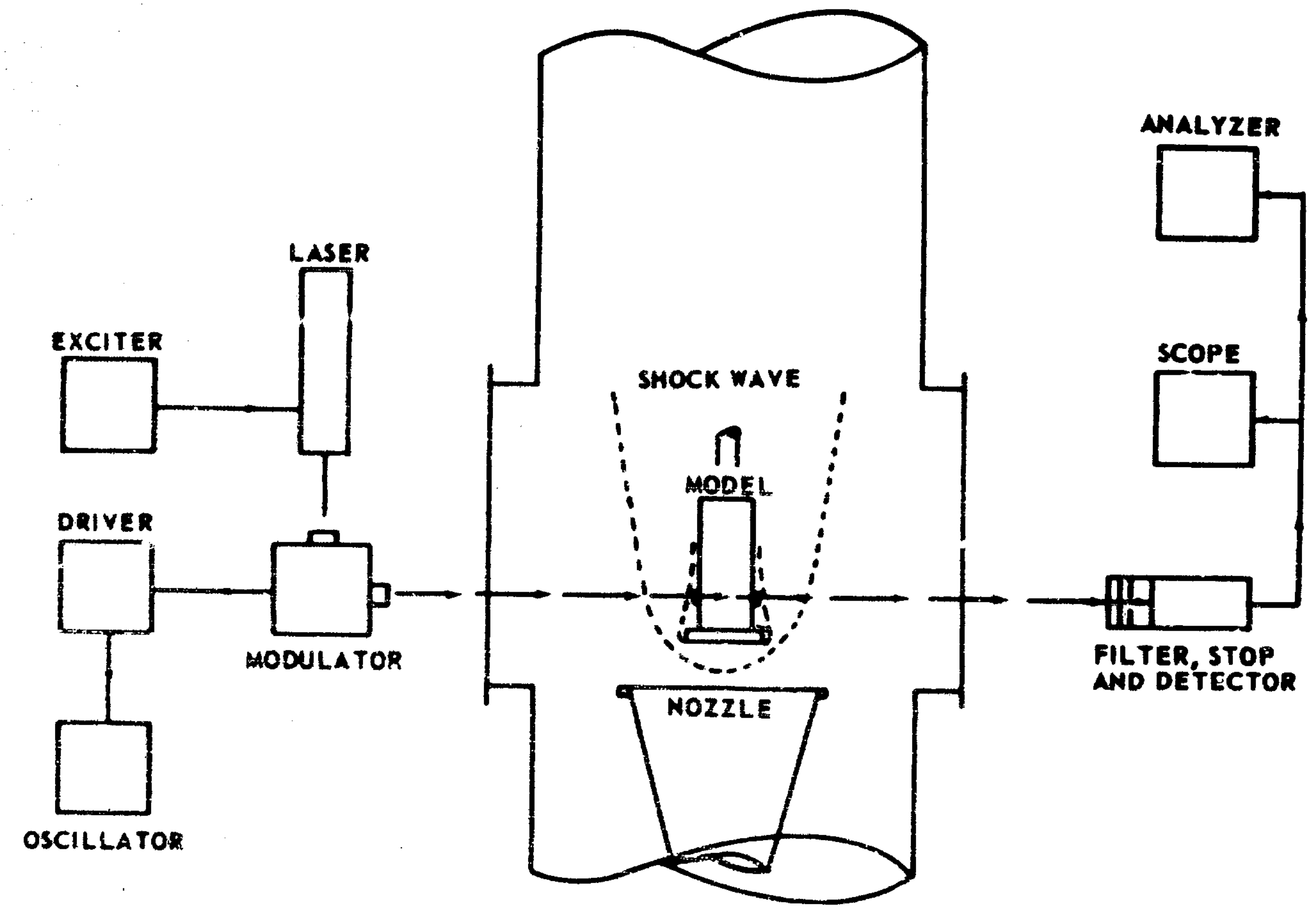



FIGURE 4. EXPERIMENTAL SETUP FOR LASER TRANSMISSION EXPERIMENTS

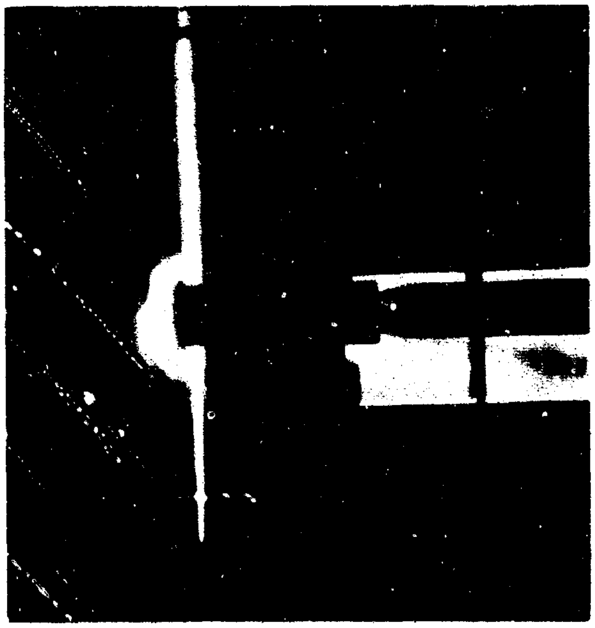


FIGURE 5. MODEL BEING TESTED IN THE PLASMA FACILITY

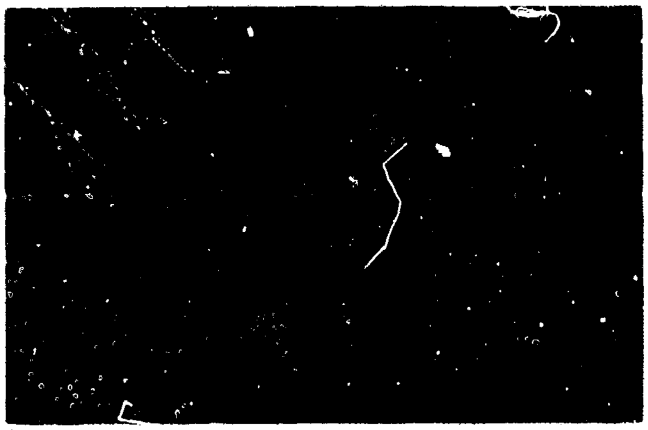


FIGURE 6. OSCILLOSCOPE TRACE

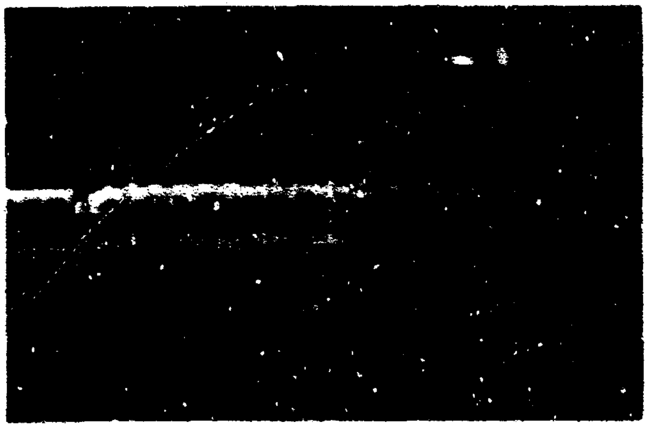


FIGURE 7. OSCILLOSCOPE TRACE

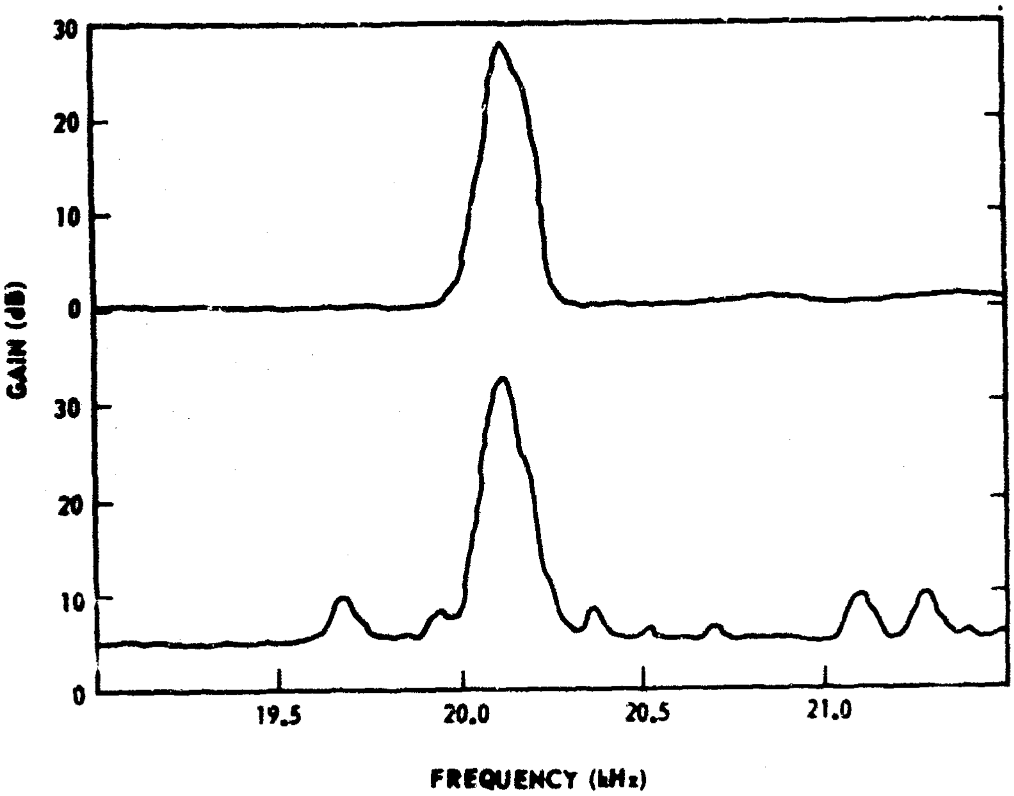
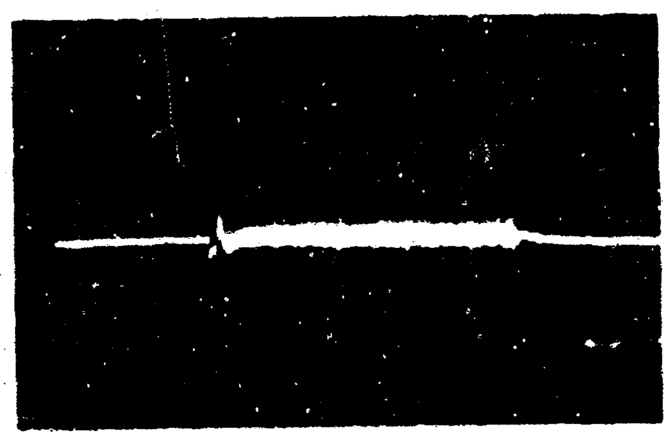



FIGURE 8. SPECTRUM ANALYZER RECORDS

SECOND TEST LASER BEAM BLOCKED 1 cm/sec



PLASMA RUNNING - START P = 100 μ

FIGURE 9. OSCILLOSCOPE TRACE

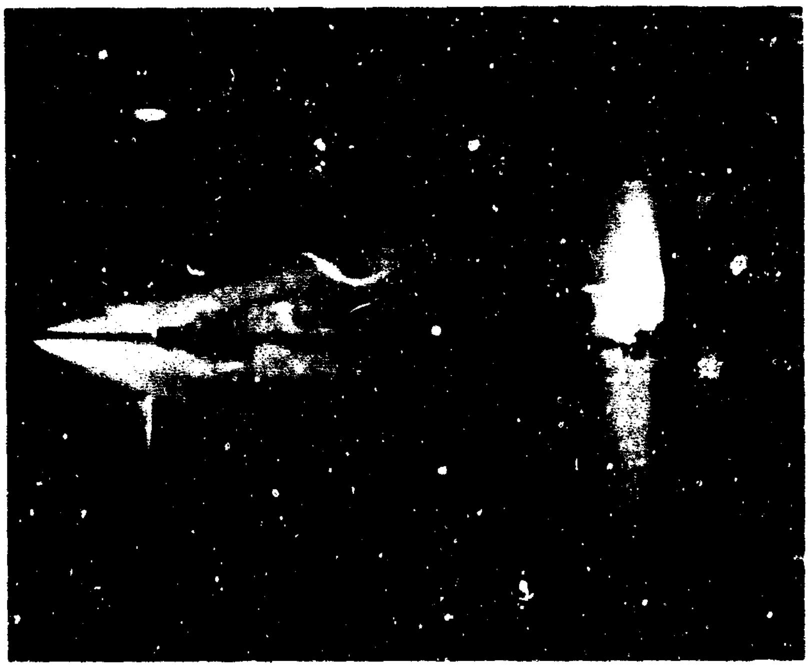


FIGURE 10. FLAT PLATE APPARATUS

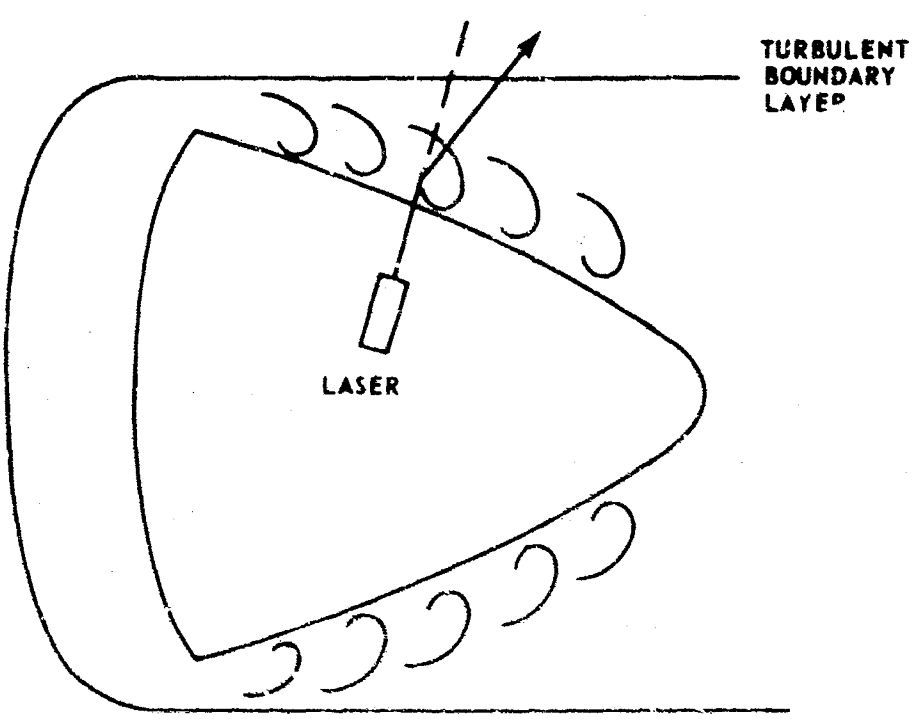



FIGURE 11. IDEALIZED FLOW FIELD AROUND A LASER CARRYING REENTRY VEHICLE

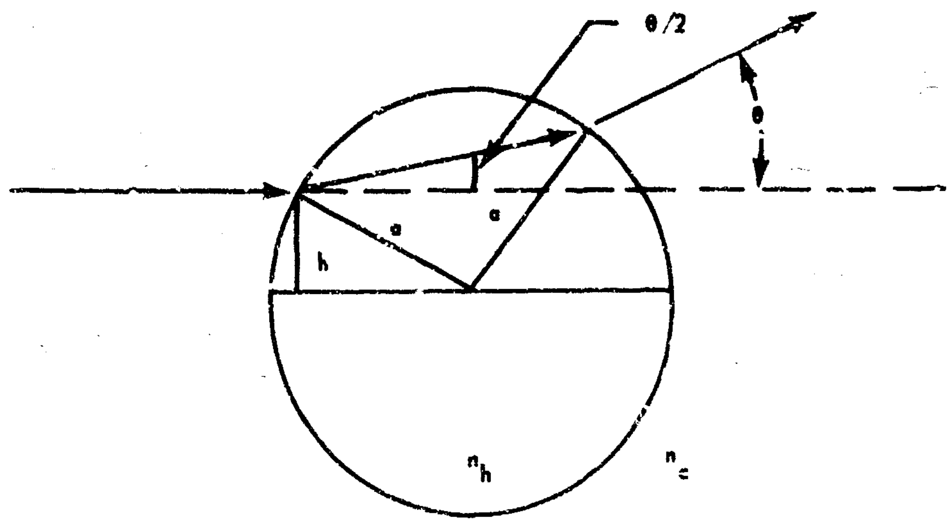



FIGURE 12. REFRACTION OF LIGHT THROUGH A CYLINDRICAL REGION

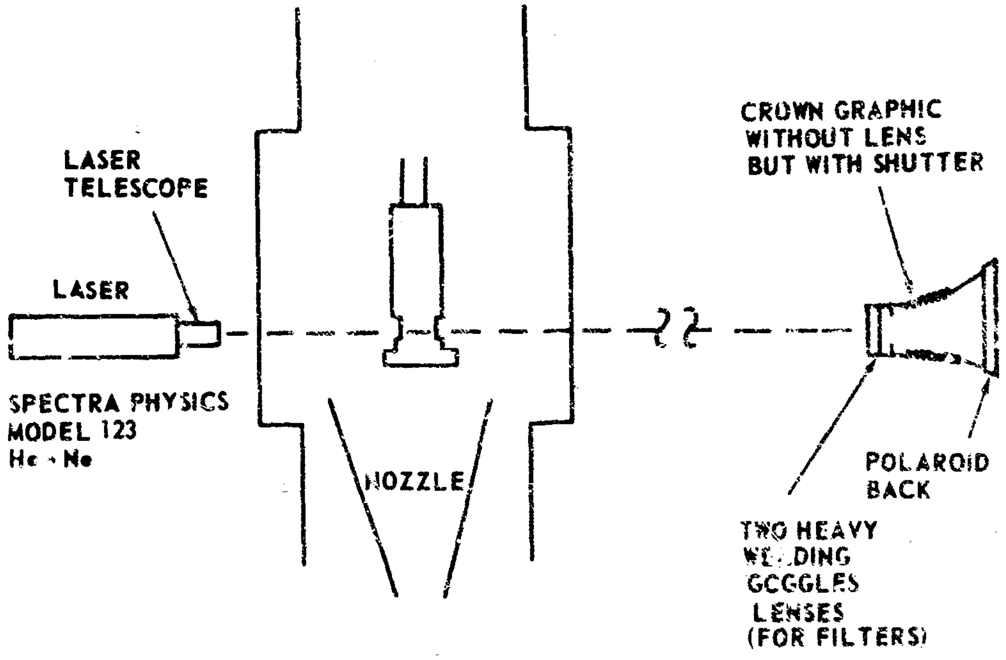



FIGURE 13. SETUP FOR LASER SCINTILLATION EXPERIMENT

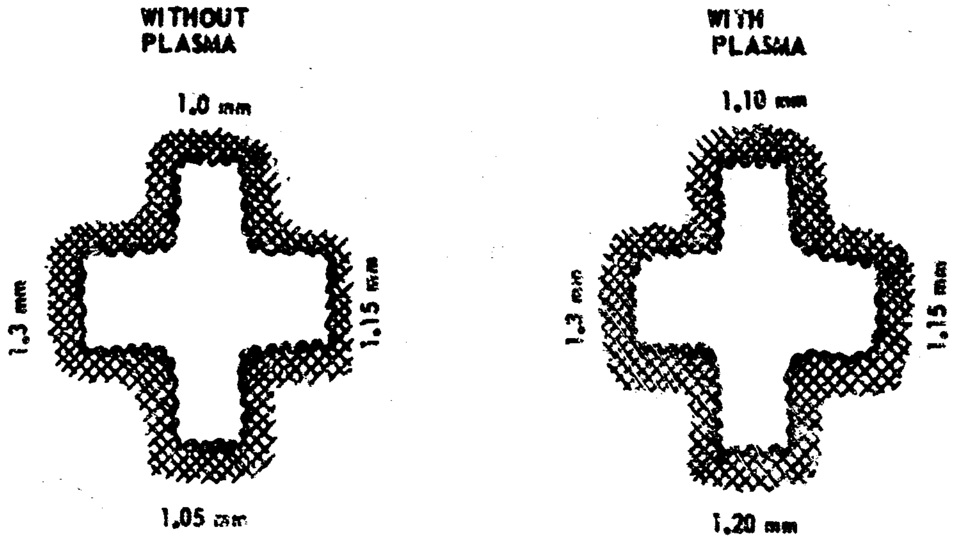
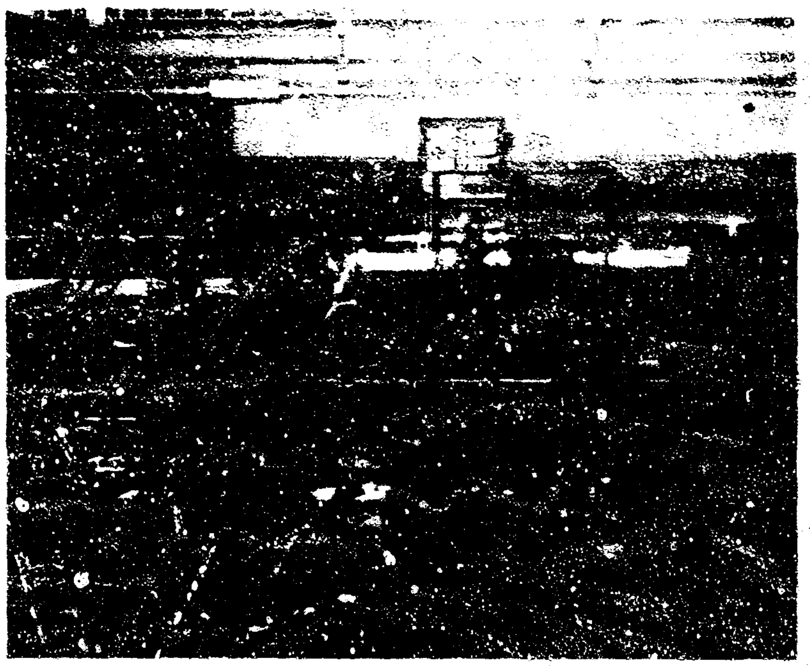



FIGURE 14. SKETCH OF LASER BEAM IMAGE



LASER CAPPED 59-mil HOLE

FIGURE 15. VIEW OF THE PLASMA FACILITY AS SEEN FROM CAMERA LOCATION

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**13. ABSTRACT**


Laser communications have been proposed as one way to solve the "radio blackout" problem during the reentry of a manned vehicle. The U. S. Army Missile Command 8000-Kilowatt Plasma Facility was used in a set of experiments to simulate the conditions expected during the reentry of a high-speed vehicle. This experimental study was designed to simulate a typical theoretical Apollo test vehicle reentry trajectory. No plasma effects on the transmitted laser beam were expected or observed. The high temperature gradients and anticipated gas density variations in the flow field were thought to be potential sources of local index-of-refraction fluctuations.

By variation of the plasma facility parameters to lower the enthalpy, the Reynolds number, or both, a satisfactory simulation of conditions just before the termination of "radio blackout" was obtained. The region of the "reentry corridor" simulated in this investigation is near a 60-kilometer per second velocity. A 0.09-meter diameter flat disk model oriented normal to the flow field was used in experiments to determine the degradation of an He-Ne laser beam modulated by a 20-kilohertz signal on a 40-megahertz carrier. Harmonic analysis of the modulation showed a small modification of the signal. A flat plate 1 meter long was also used in experiments to determine beam deflection by the flow field due to index of refraction fluctuations. Beam deflection was $< 10^{-5}$ radians.


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| Apollo test vehicle | | | | | | |
| Plasma effects | | | | | | |
| Radio blackout | | | | | | |